NSF CPS Synergy: Collaborative Research: Towards Effective and Efficient Sensing-Motion Co-Design of Swarming Cyber Physical Systems

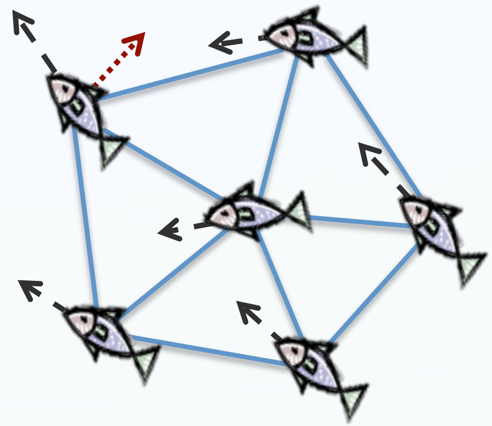
Duration: January, 2015 - January 2018

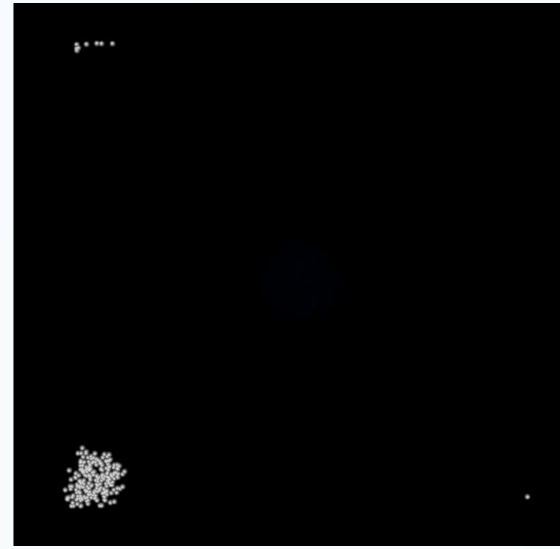
Rensselaer

Wichita State University

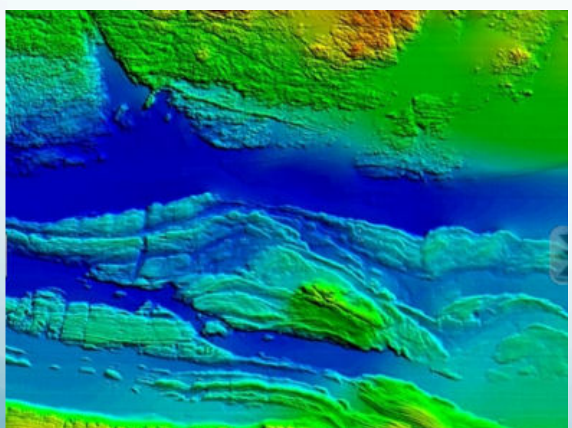
University at Buffalo
The State University of New York

Swarming Cyber-Physical Systems (CPS)



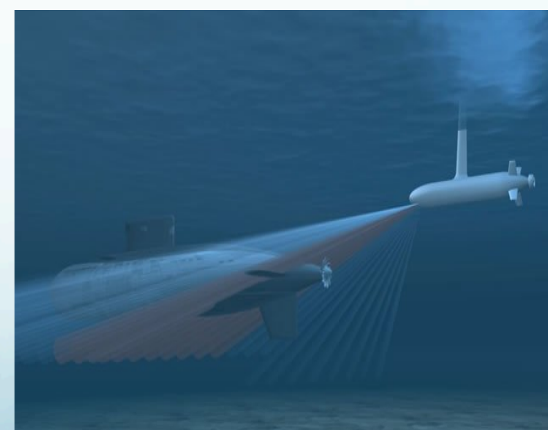


Berdahl, Torney, Ioannou, Faria, & Couzin, *Science,* 2013



Environmental mapping

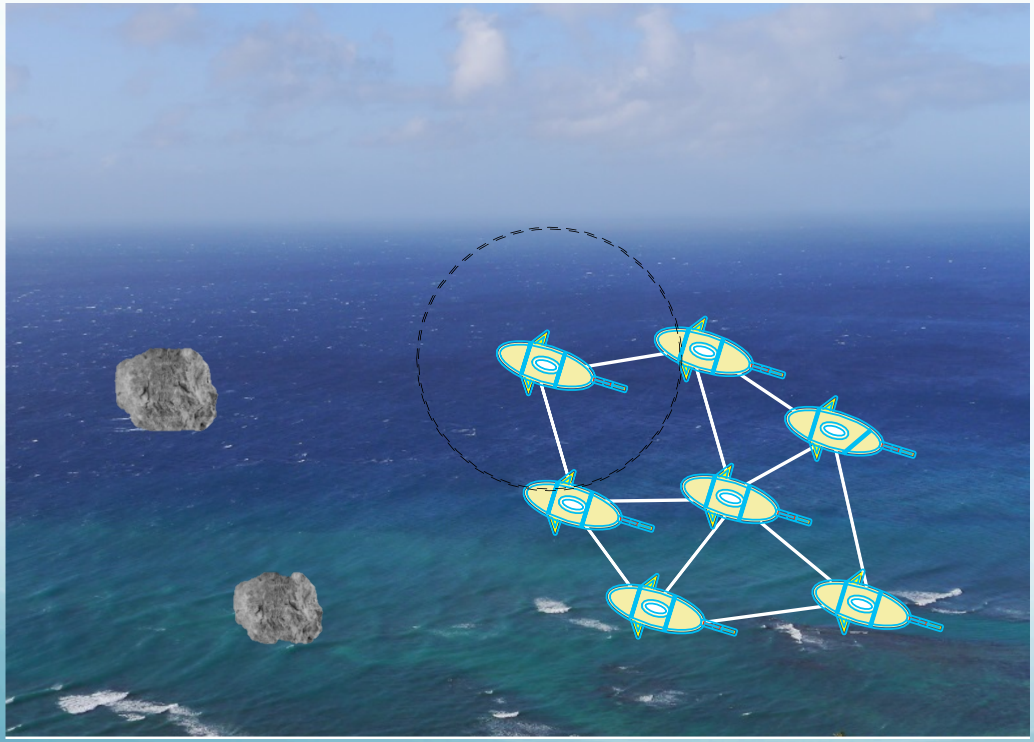
Source seeking



Tracking

Grant Challenges and Objectives

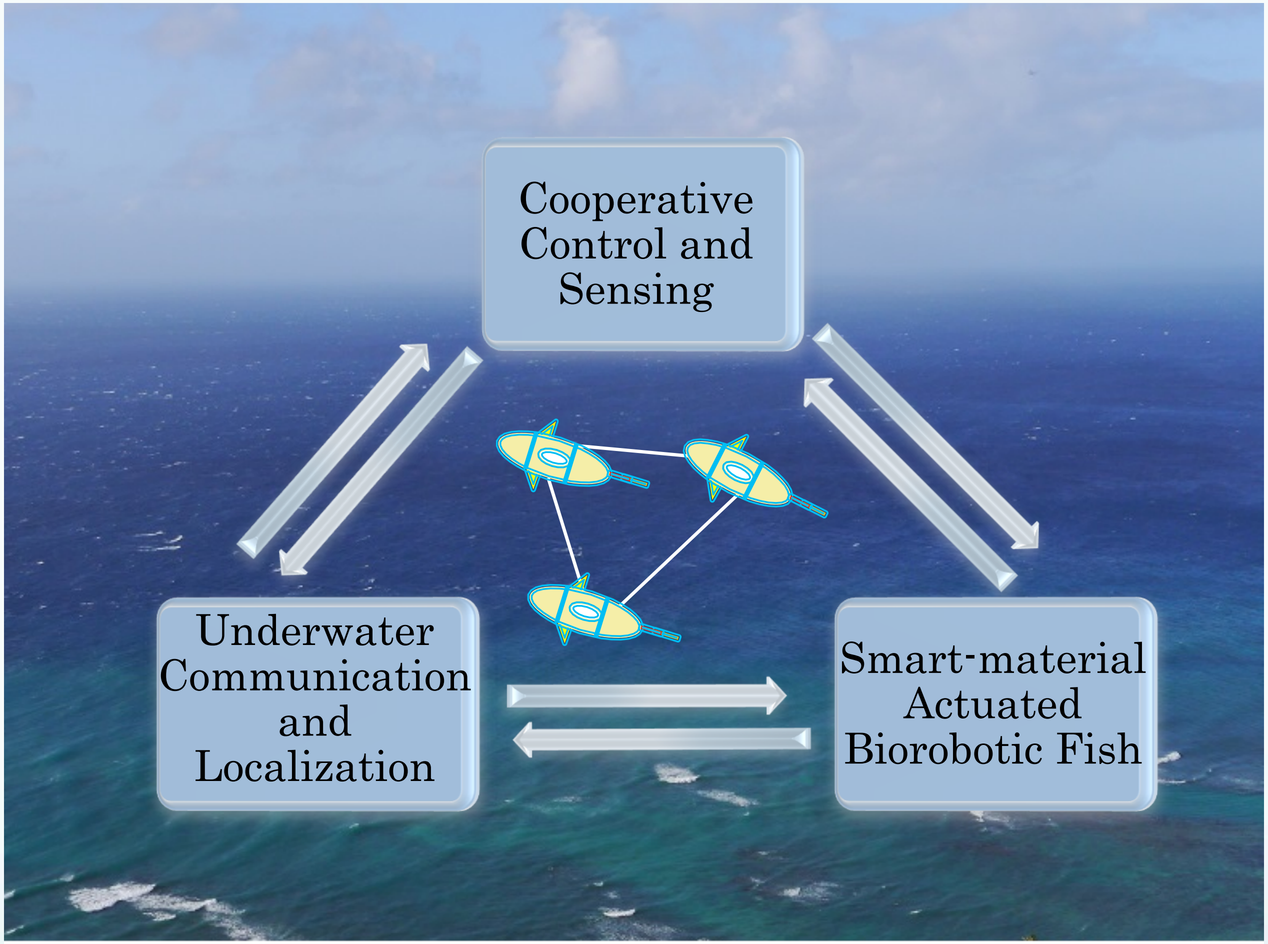
Objective: establish and demonstrate a generic motion-sensing co-design procedure that significantly reduces the complexity of mission design for swarming CPS, and greatly facilitates the development of effective and efficient control and sensing strategies.



Challenges

- Inherent environmental uncertainties
- Complex and strongly coupled sensing-motion dynamics
- Harsh environments
- Resource constraints of mobile entities

Key Contributions



- Offer **comprehensive scientific understanding** of the interplay between sensing and motion dynamics of swarming CPS
- Contribute to **generic engineering principles** for designing collaborative control strategies for increasingly complex CPS missions
- Advance the **enabling technology** of practically applying CPS in the challenging but emerging environments

The Team

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University at Buffalo
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Zhi Sun

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Animesh Chakravarthy

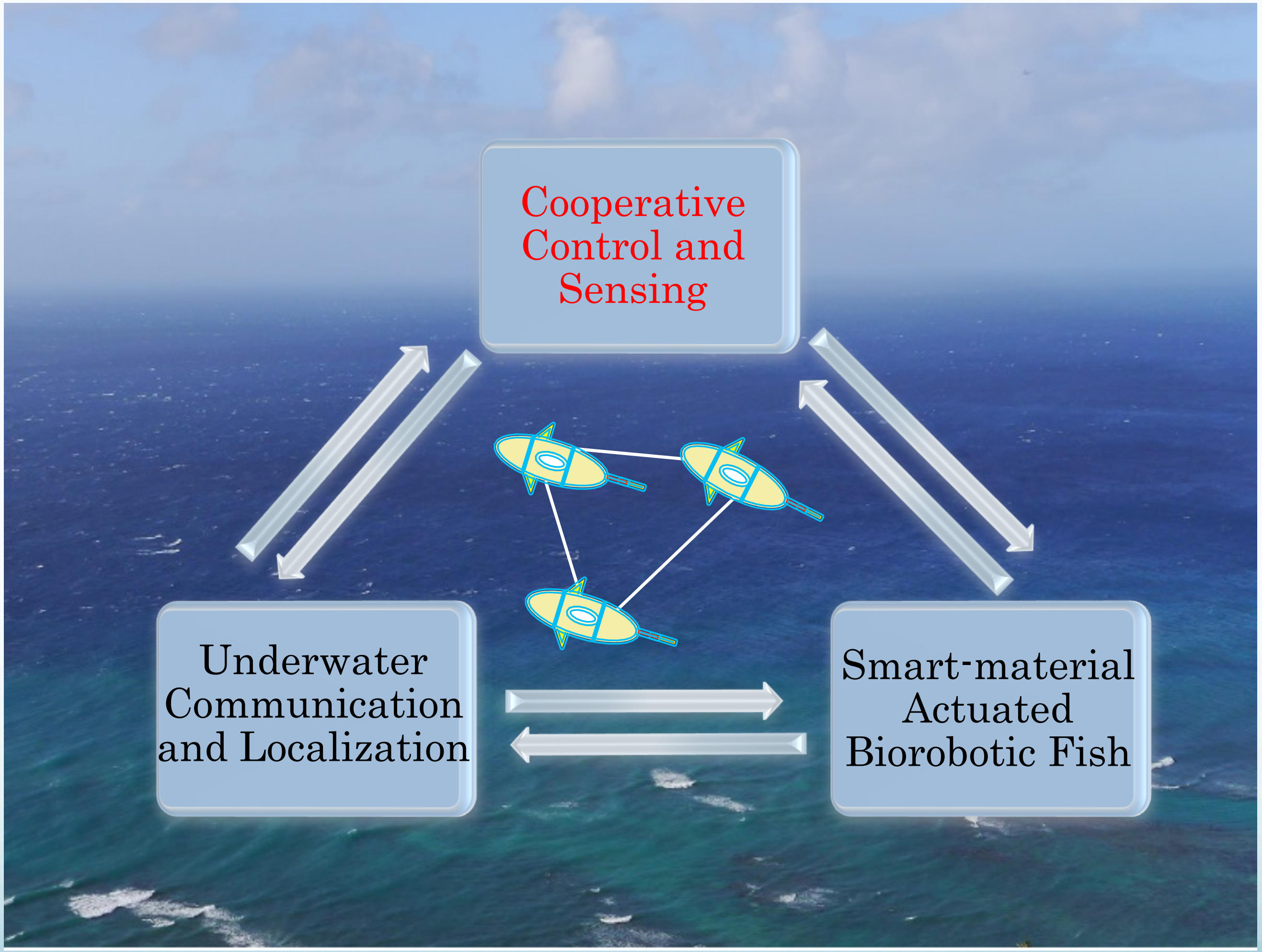
Zheng Chen

Control

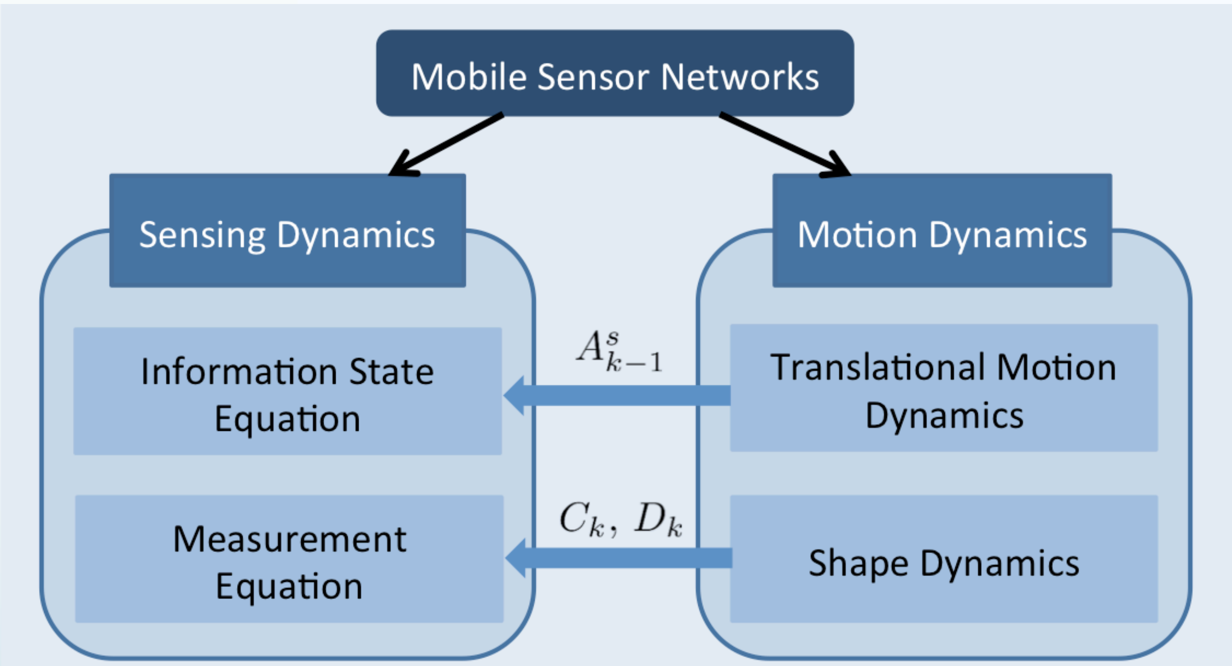
Communication/Networking

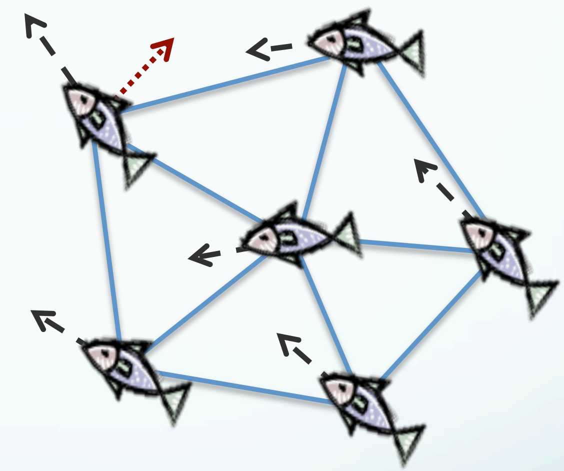
Robotics

Key Contributions



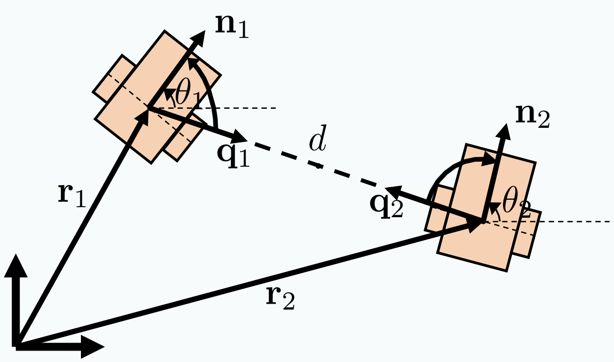
A Generic Motion-Sensing Co-design Procedure

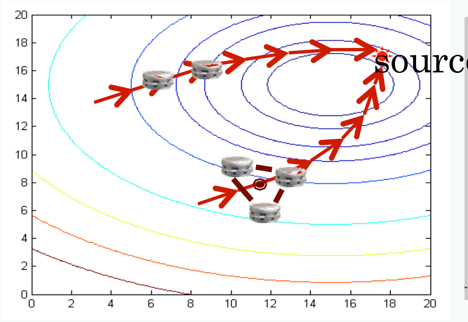


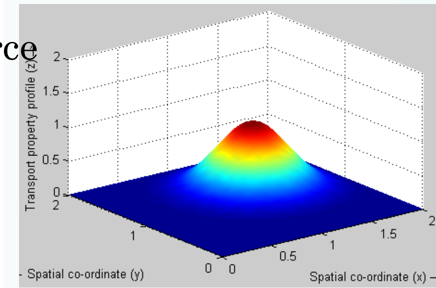


Gradient Free Source Seeking – The SUSD Strategy

- **Provably-correct Distributed Velocity Control Laws**
  - Modulate linear velocity (forward speed) only according to its local measurements to achieve source seeking
  - Control angular velocity to maintain a desired formation with one-hop neighbors







- **Key attributes**
  - limited resources-required
  - fast convergence in 2D/3D scalar fields
  - robust under deterministic/stochastic perturbations

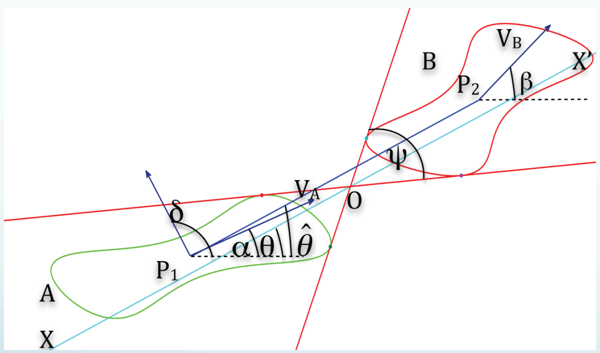
W. Wu and F. Zhang, "A Speeding-up and Slowing-down Strategy for Distributed Source Seeking with Robustness Analysis", *IEEE Transactions on Control of Networked Systems*, in print, 2015

L. Lu, J. You, and W. Wu, "Constrained Fast *Source Seeking Using Two Nonholonomic Mobile Robots", submitted to* American Control Conference, under review, 2016

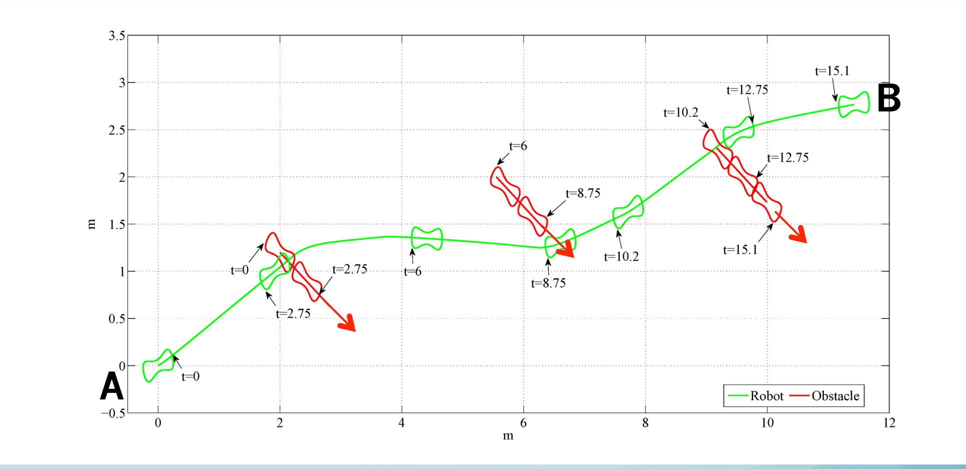
Collision Avoidance

- Collision avoidance is an important requirement in vehicle swarms.
  - Inter-swarm collision avoidance
  - Intra-swarm collision avoidance

- We propose to employ the collision cone approach to determine analytical guidance laws for collision avoidance.
  - Computational light
  - More space freedom without circles/polygons applications
  - Applicable for 3-D maneuver through a small mobile/static orifice

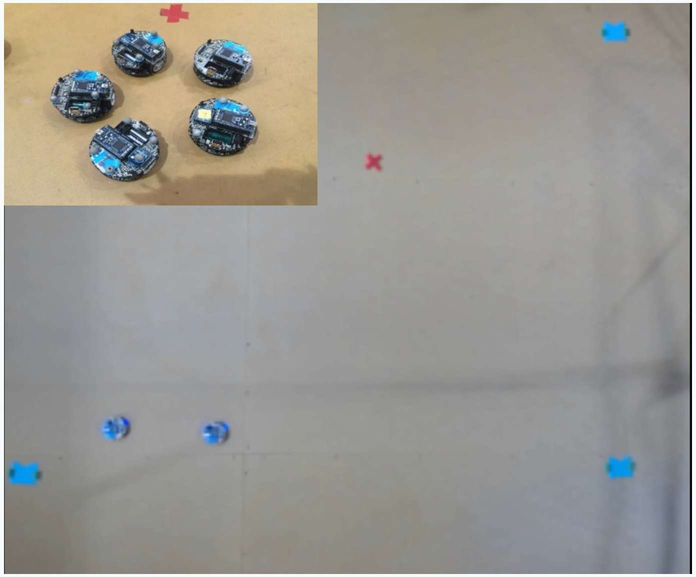


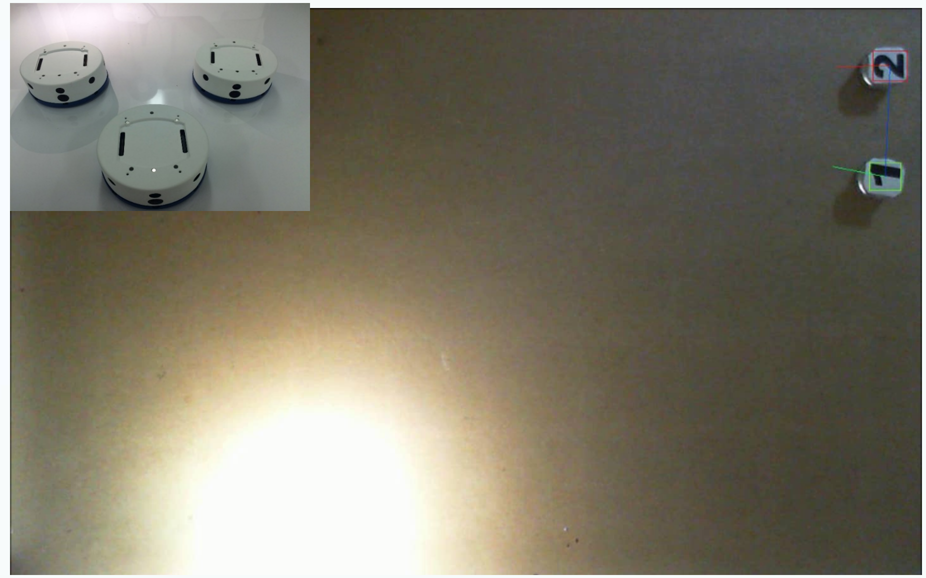
Collision Between Objects of Arbitrary Shapes

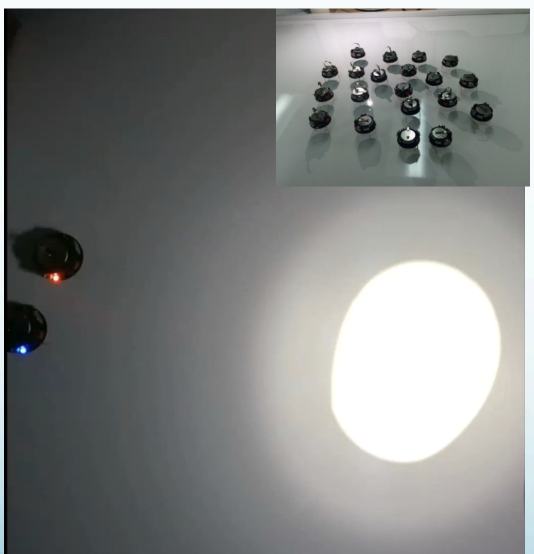


A. Chakravarthy and D. Ghose, "Guidance Laws for Precision 3-D Maneuvers through an Orifice using Safe Passage Cones", submitted to Journal of Guidance, Control and Dynamics, under review.

#V. Sunkara and A. Chakravarthy, "Collision Avoidance Laws for Objects with Arbitrary Shapes", submitted to American Control Conference 2016, under review.







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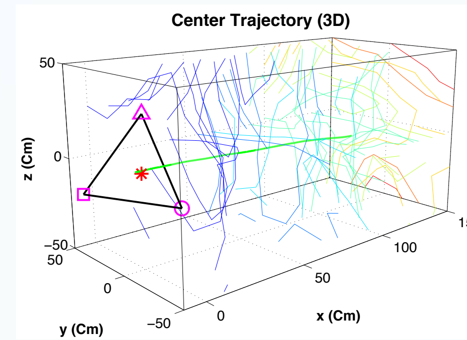
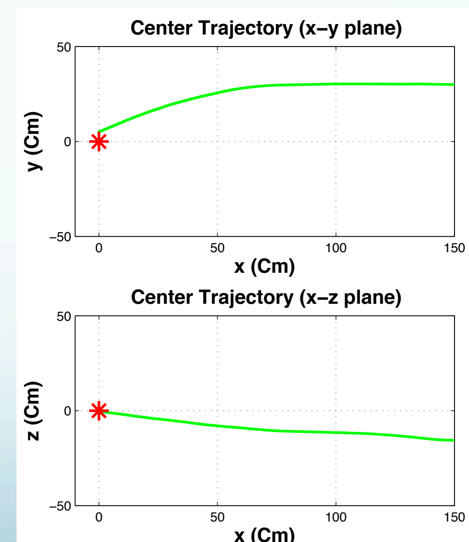
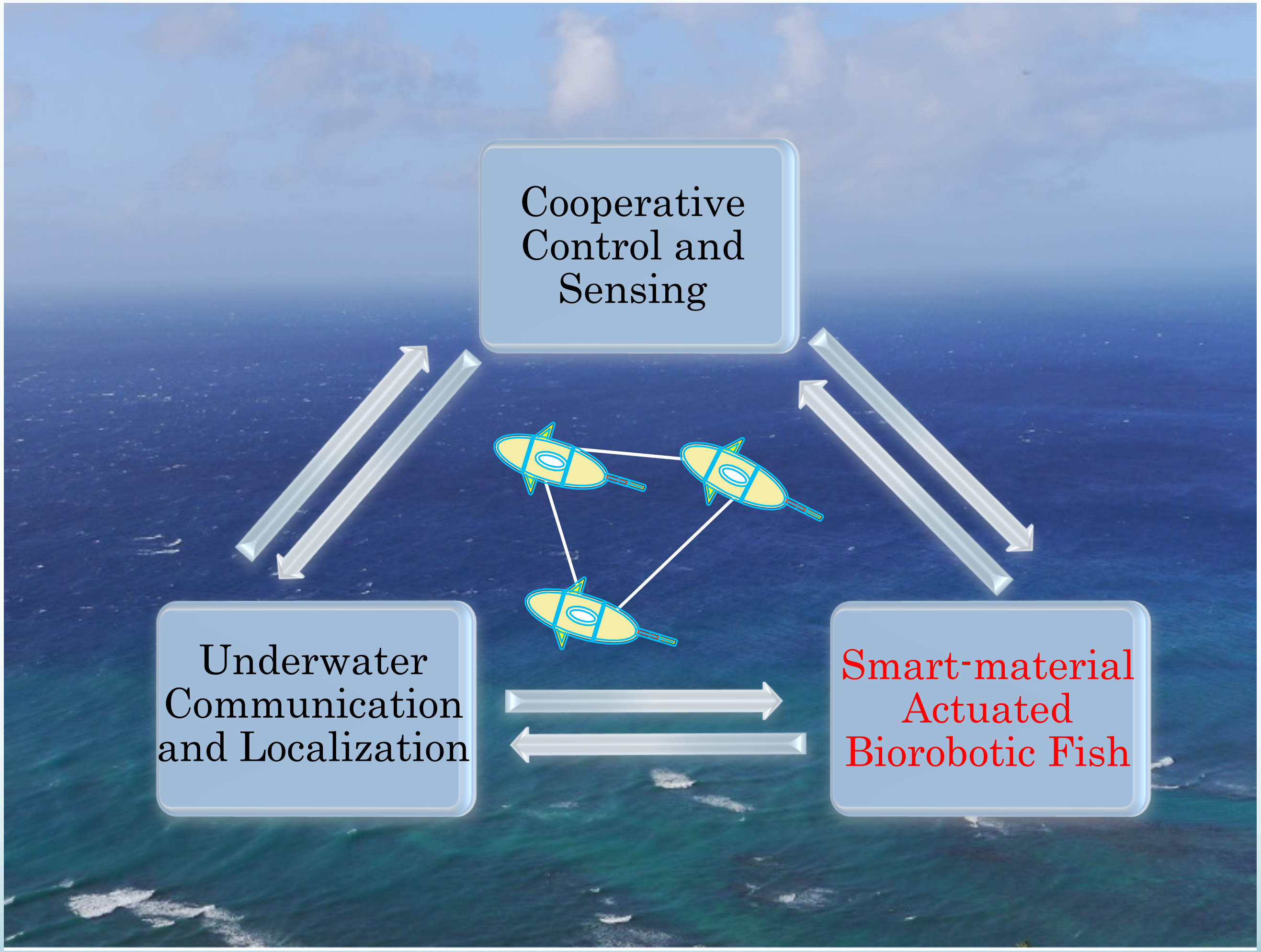
Simulation Results in 3D

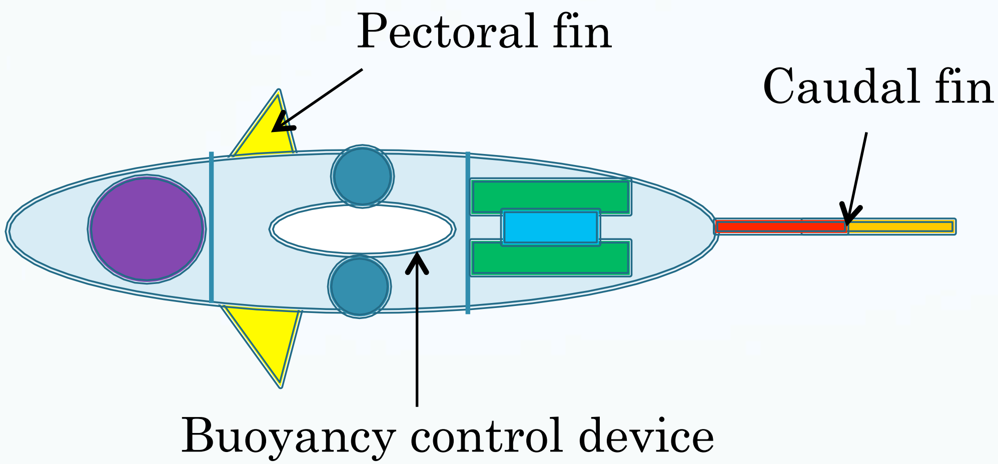




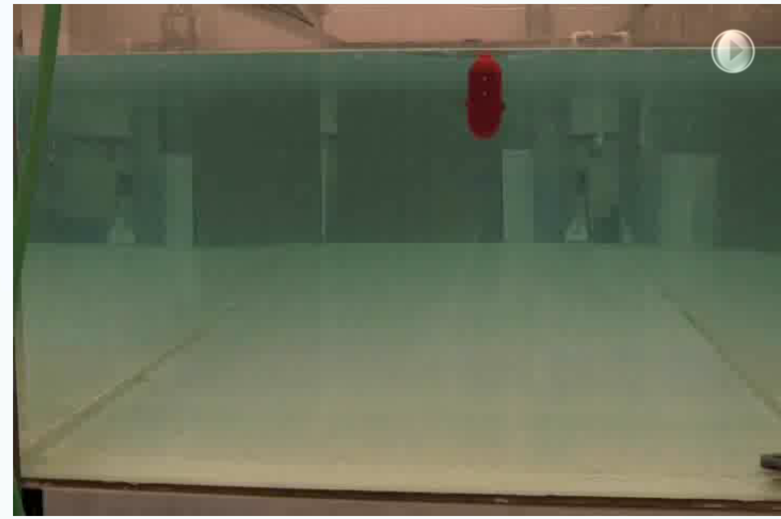
Key Contributions



Smart Material Actuated 3D Maneuverable Robotic Fish

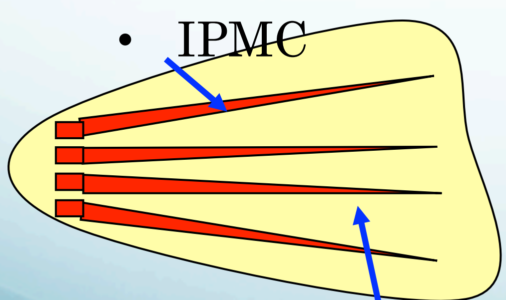


Overall Design

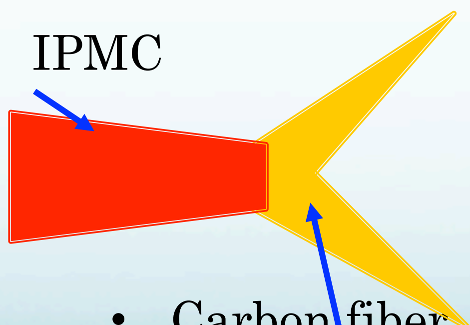


IPMC Enabled Water Electrolysis

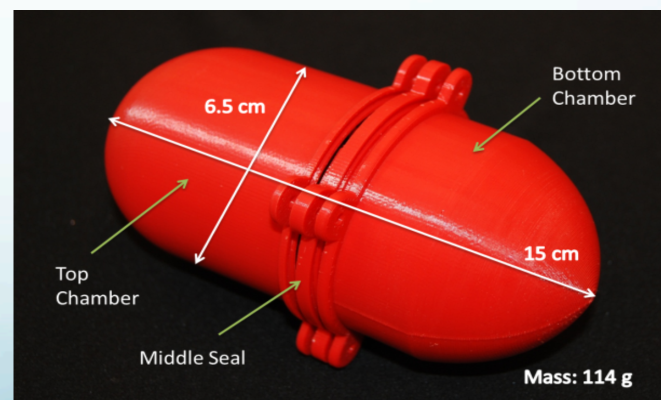
Novelty: Ionic Polymer-Metal Composites (IPMCs) are used as artificial muscle and electrolyzer.



Pectoral Fin



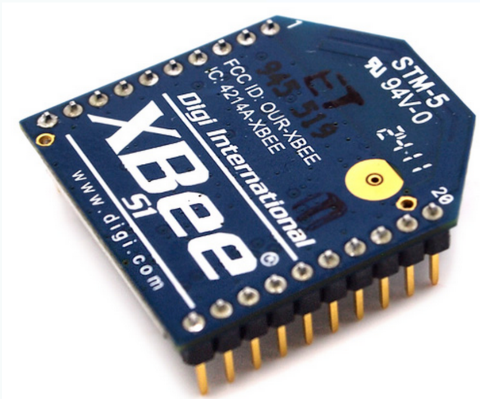
Caudal Fin



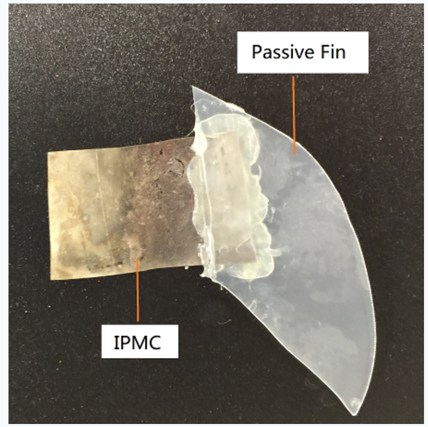
Buoyancy Control Device

(Um et al, 2011)

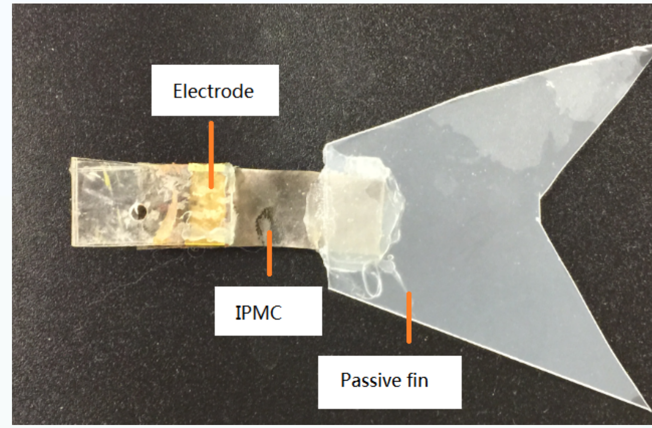
Fabrication Result



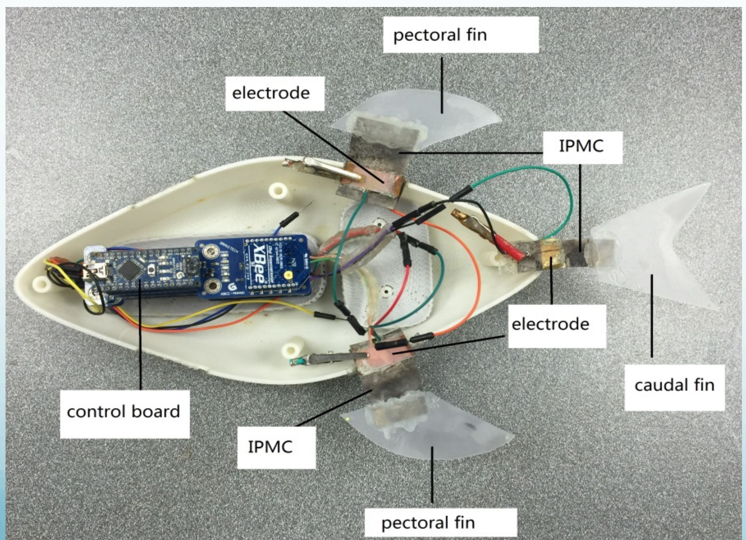
Xbee communication



Pectoral fin

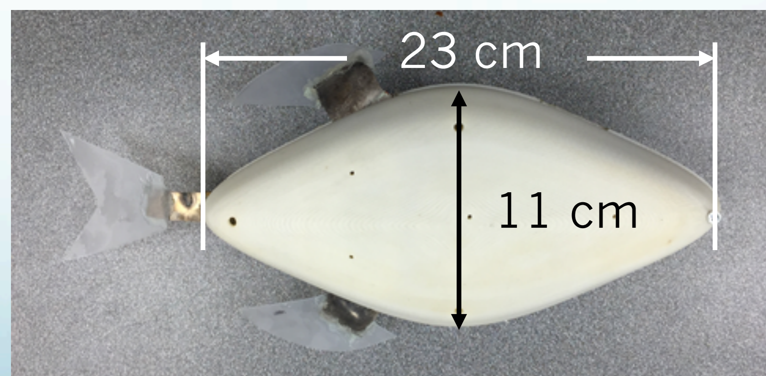


Caudal fin



Inside the robotic fish

- The total weight of the robot: 290 grams

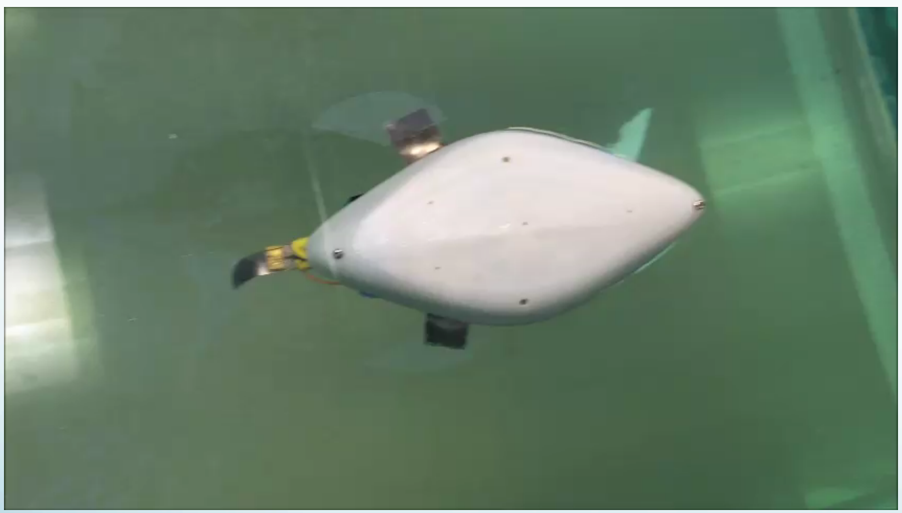


Assembled robotic fish

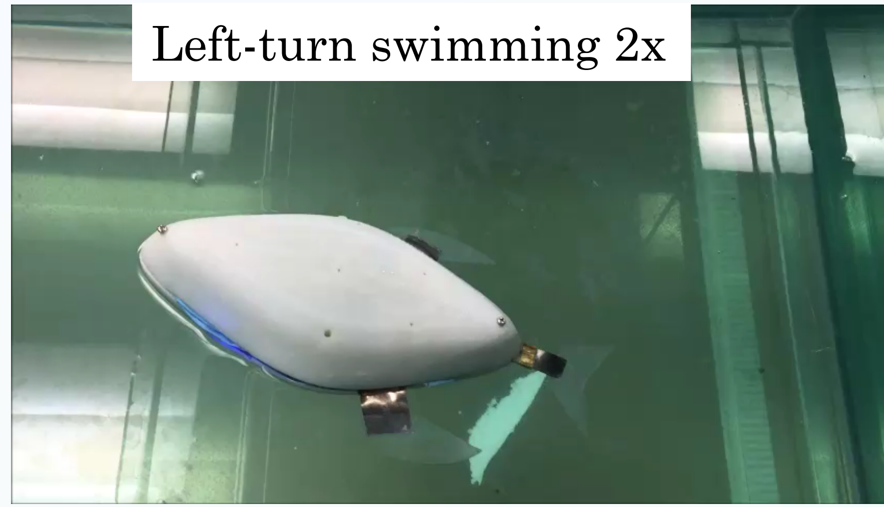
Swimming Test

T. Yang and Z. Chen, "**Development of 2D Maneuverable Robotic Fish Propelled By Multiple Ionic Polymer-Metal Composite Artificial Fins** " Proc. of the 2015 IEEE Conference on Robotics and Biomimetics, Zhuhai, China, to appear, 2015

The forward-swimming speed reached 0.5 cm/sec, and both the left-turning and right-turning speeds reached up to 1.5 rad/sec.

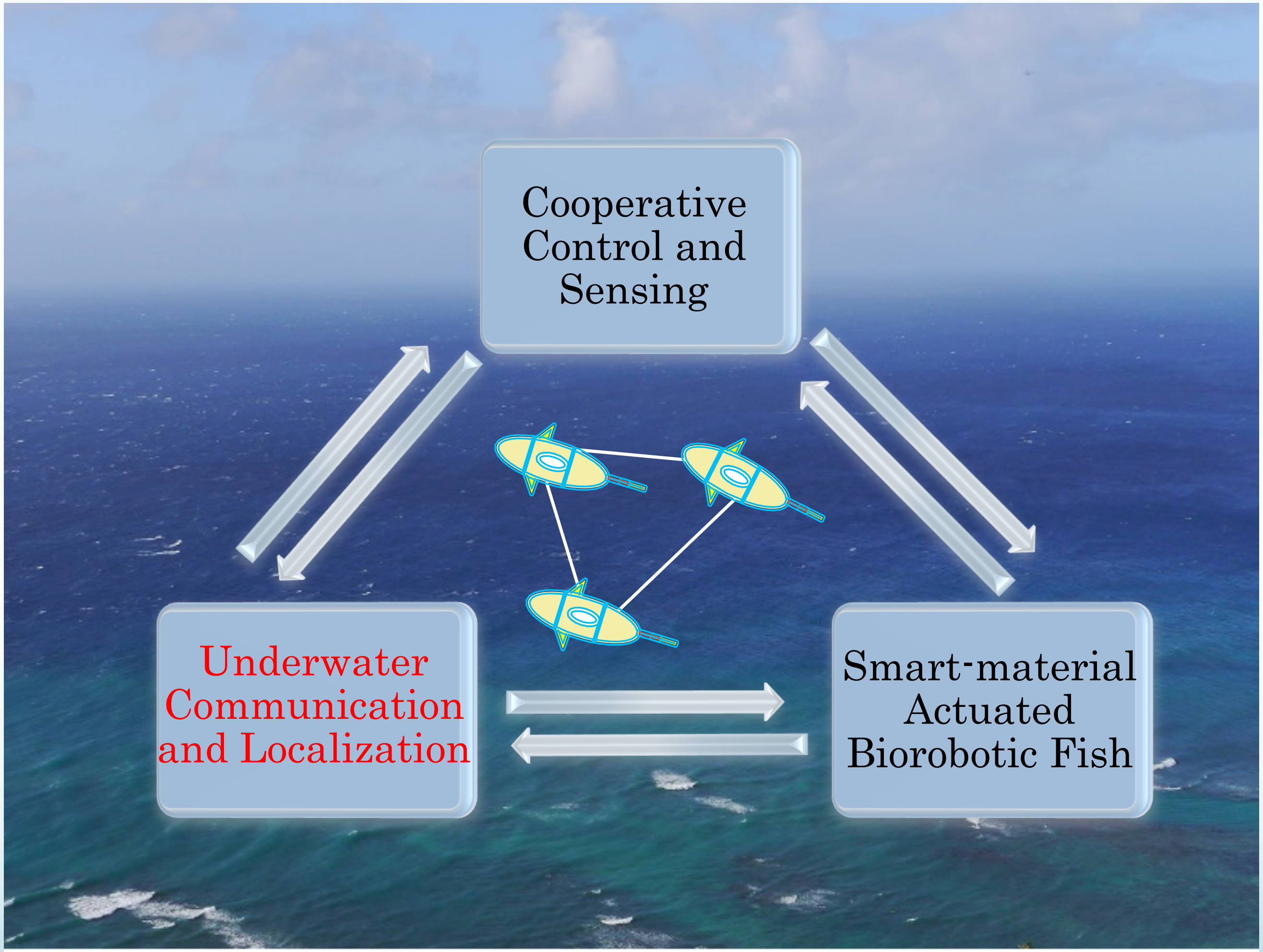


Forward swimming 2x



Left-turn swimming 2x

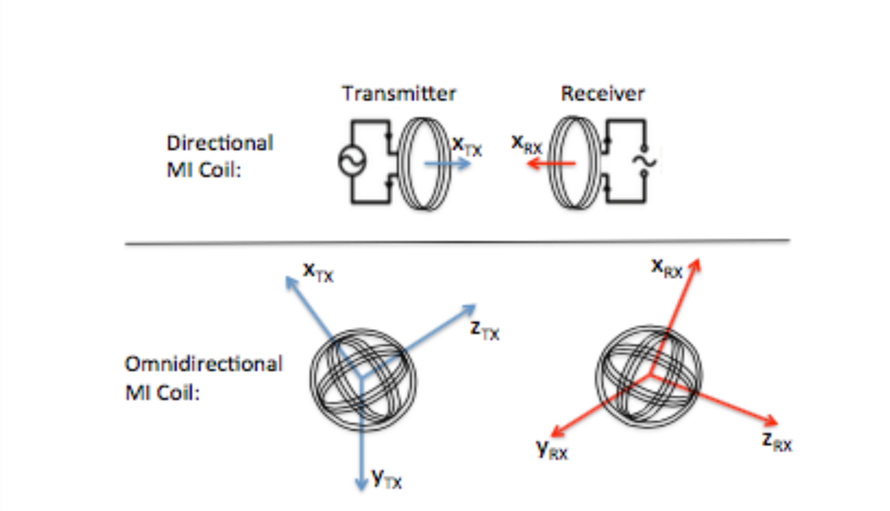
Right-turn swimming 2x


Cooperative Control and Sensing
Underwater Communication and Localization
Smart-material Actuated Biorobotic Fish

MI Underwater Communications & Localization

I. F. Akyildiz, P. Wang, and Z. Sun, "Realizing Underwater Communication through Magnetic Induction", to appear in IEEE Communications Magazine, 2015.

- MI communication is realized by a time varying magnetic field through novel 3D coil antenna

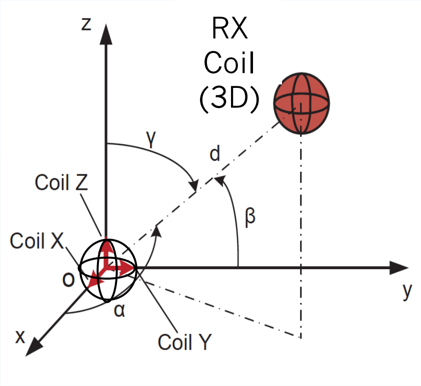


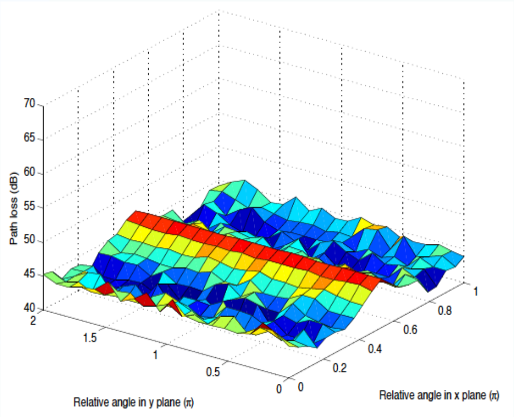
- **Key advantages:**
  - negligible signal propagation delay
  - large bandwidth (~ MHz)
  - sufficiently long transmission range (~ hundred meters)
  - very small (~ centimeters) & low cost coil antenna (~ 1 dollar per unit)
  - highly constant & predicable channel response in harsh underwater environment
    * shallow water
    * confined & cluttered UW structures

Underwater MI Channel Model

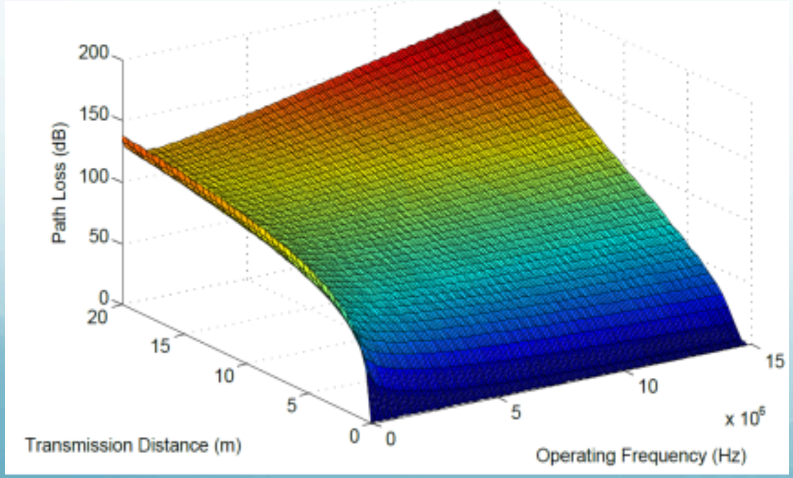
H. Guo, Z. Sun, and P. Wang, "Channel modeling of MI UW communication using tri-directional coil antenna," in Proc. IEEE Globecom 2015, San Diego, USA, 2015

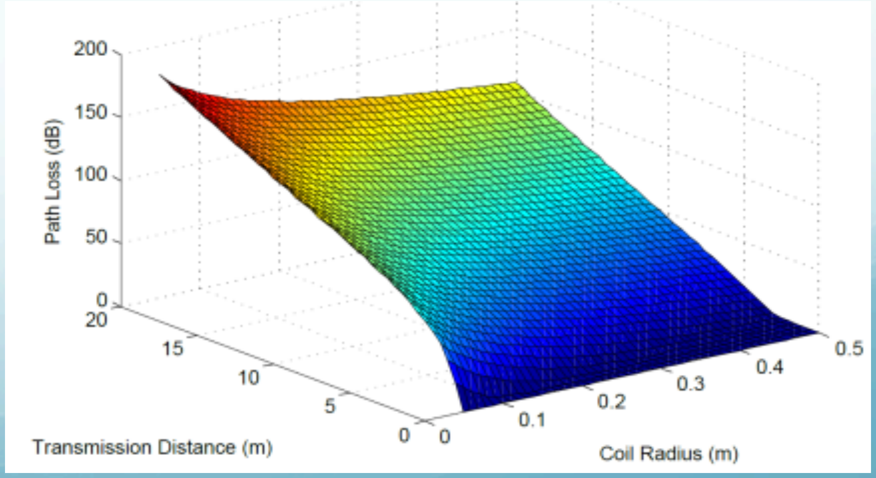
- MI antenna with 3 orthogonal coils
  - Omni-directional communication
  - Rigorous channel model reveals:
    - 20 m communication range
    - Optimal frequency at 10 MHz
    - Small coil (10 cm in diameter)
  - Can be used for 3D localization





Pathloss independent of relative locations between sensors





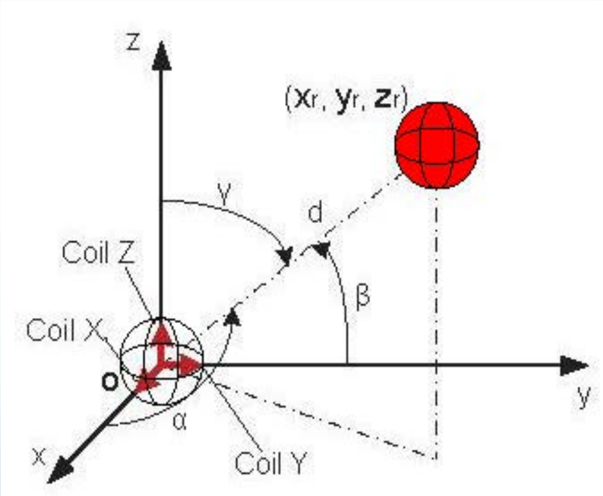
Underwater Software-Defined Radio Testbed

MI-based Relative Localization

X. Tian, Z. Sun, and P. Wang, "On Localization for Magnetic Induction-based Wireless Sensor Networks in Pipeline Environments," in Proc. of IEEE ICC, June 2015.

- Multi-path fading-free MI channel & orthogonality of tri-coil MI antennas

→ accurate, simple, convenient localization



Next Steps

- The integration of control, sensing, communication, and localization in robotic fish
- Implementation of the source-seeking and collision avoidance strategies in robotic fish
- 3D maneuverable robotic fish design & optimization
- MI transceiver optimization and protocol design

Publications Resulted from this Project
01/2015 – 11/2015

- I. F. Akyildiz, P. Wang and Z. Sun, "**Realizing Underwater Communication through Magnetic Induction,**" to appear in IEEE Communications Magazine, Sept. 2015
- H. Guo, Z. Sun and P. Wang , "**Channel Modeling of MI Underwater Communication using Tri-directional Coil Antenna**" to appear in IEEE GLOBECOM 2015, San Diego, CA, Dec. 2015;
- S. Xia and P. Wang, "**Distributed Throughput Optimal Scheduling in the Presence of Heavy-Tailed Traffic**" in Proc. of IEEE ICC 2015, London, UK, June 2015;
- X. Tian, Z. Sun and P. Wang , "**On Localization for Magnetic Induction-based Wireless Sensor Networks in Pipeline Environments**" in Proc. of IEEE ICC 2015, London, UK, June 2015;
- S. Xia, P. Wang and Z. Sun, "**Distributed Timely-Throughput Optimal Scheduling for Wireless Networks**" to appear in IEEE GLOBECOM 2014, Austin, Texas, USA, Dec 2014;
- Z. Chen, "**A Review on Robotic Fish Enabled by Ionic Polymer-Metal Composite Artificial Muscle**", Robotics and Biomimetics, to appear, 2015
- T. Yang and Z. Chen, "**Development of 2D Maneuverable Robotic Fish Propelled By Multiple Ionic Polymer-Metal Composite Artificial Fins** " Proc. of the 2015 IEEE Conference on Robotics and Biomimetics, Zhuhai, China, to appear, 2015
- T. Nagpure and Z. Chen, "**Modeling of Ionic Polymer-Metal Composite Enabled Hydrogen Gas Production**", Proc. of the ASME 2015 Dynamic Systems and Control Conference, Columbus, Ohio, Paper Number: DSCC2015-9922, pp. 1-8, 2015
- W. Wu and F. Zhang, "**A Speeding-up and Slowing-down Strategy for Distributed Source Seeking with Robustness Analysis**", IEEE Transactions on Control of Networked Systems, in print, 2015
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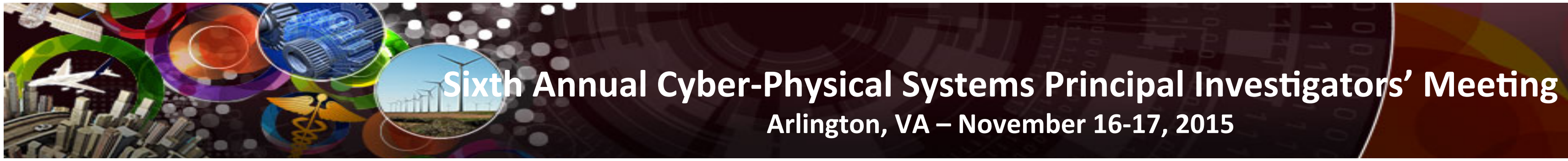
- J. You, F. Zhang, and W. Wu, "**Cooperative Filtering for Parameter Identification of Diffusion Processes**", submitted to American Control Conference, under review, 2016.
- A. Chakravarthy and D. Ghose, "**Guidance Laws for Precision 3-D Maneuvers through an Orifice using Safe-Passage Cones**", submitted to Journal of Guidance, Control and Dynamics, under review.
- K. Tholen and A. Chakravarthy, "**Analytical Laws for Area Coverage by Robot Networks**", under preparation for submission to Journal of Guidance, Control and Dynamics.
- #V. Sunkara and A. Chakravarthy, "**Collision Avoidance Laws for Objects with Arbitrary Shapes**", submitted to American Control Conference 2016, under review.



Towards Effective and Efficient Sensing-Motion Co-Design of Swarming Cyber Physical Systems

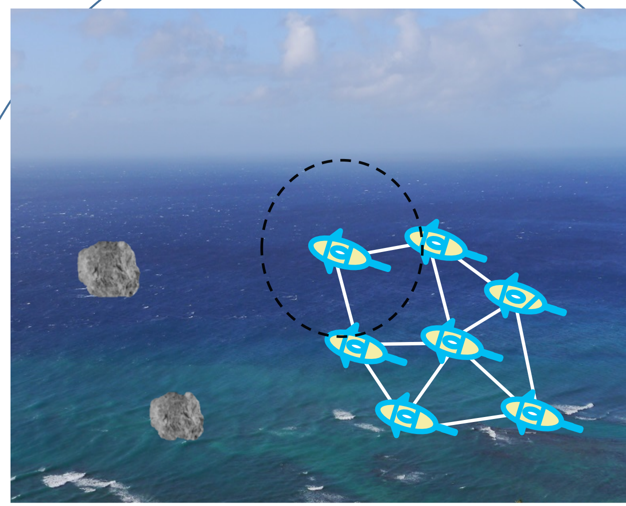
(Rensselaer Polytechnic Institute, Wichita State University, SUNY Buffalo)

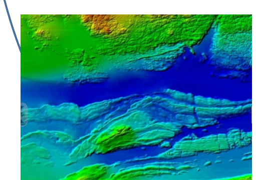
Challenge:

- Inherent environmental uncertainties
- Complex and strongly coupled sensing-motion dynamics
- Harsh environments
- Resource constraints of mobile entities

Solution:

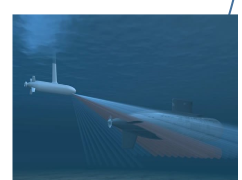
- Cooperative sensing and control strategy
- Smart material actuated robotic fish
- MI-based underwater communication and localization





Mapping

Source seeking



Tracking

Scientific Impact:

- Understanding of the coupled sensing and motion dynamics
- Generic engineering principles for designing collaborative control and sensing strategies
- Enabling technology of applying CPS in challenging environments

Broader Impact:

- Advance in the environmental sustainability, homeland security, and human well-being
- Course integration
- Student training

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CNS 1556557: PI: Pu Wang, co-PI: Zheng Chen, Animesh Chakravarthy, Wichita State
CNS 1446484: PI: Zhi Sun, SUNY Buffalo